THE MEASUREMENT OF EARTH RESISTIVITY AFFECTING MHD-EMP RESPONSE OF BURIED CABLES

J. W. Erler
V. A. J. van Lint
Mission Research Corporation
5434 Ruffin Road
San Diego, California 92123

1 December 1980

AD A131253

Topical Report for Period 1 April 1980—30 November 1980

CONTRACT No. DNA 001-80-C-0215

APPROVED FOR PUBLIC RELEASE;
DISTRIBUTION UNLIMITED.

DTIC FILE COPY

DTIC
ELECTE
1 1 1983
B

Prepared for
  Director
  DEFENSE NUCLEAR AGENCY
  Washington, DC 20305

88 07 01 014

Destroy this report when it is no longer
needed. Do not return to sender.

PLEASE NOTIFY THE DEFENSE NUCLEAR AGENCY,
ATTN: STTI, WASHINGTON, D.C. 20305, IF
YOUR ADDRESS IS INCORRECT, IF YOU WISH TO
BE DELETED FROM THE DISTRIBUTION LIST, OR
IF THE ADDRESSEE IS NO LONGER EMPLOYED BY
YOUR ORGANIZATION.

REPORT DOCUMENTATION PAGE	READ INSTRUCTIONS BEFORE COMPLETING FORM	
1. REPORT NUMBER DNA 5530T	2. GOVT ACCESSION NO. *A131253*	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) THE MEASUREMENT OF EARTH RESISTIVITY AFFECTING MHD-EMP RESPONSE OF BURIED CABLES	5. TYPE OF REPORT & PERIOD COVERED Topical Report for Period 1 Apr 80—30 Nov 80	
	6. PERFORMING ORG. REPORT NUMBER MRC/SD-R-69	
7. AUTHOR(s) J.W. Erler V.A.J. van Lint	8. CONTRACT OR GRANT NUMBER(s) DNA 001-80-C-0215	
9. PERFORMING ORGANIZATION NAME AND ADDRESS Mission Research Corporation 5434 Ruffin Road San Diego, CA 92123	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Subtask X99QAXVC301-04	
11. CONTROLLING OFFICE NAME AND ADDRESS Director Defense Nuclear Agency Washington, D.C. 20305	12. REPORT DATE 1 December 1980	
	13. NUMBER OF PAGES 38	
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)	15. SECURITY CLASS (of this report) Unclassified	
	15a. DECLASSIFICATION DOWNGRADING SCHEDULE N/A since unclassified	

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Magneto-telluric
Earth Resistivity
Magneto-hydrodynamic Electromagnetic Pulse
Resistivity Methods

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The response of buried conducting cable to a MHD EMP wave is determined in part by the resistivity of the earth at frequencies ranging from 10 to 0.01 Hz. Three methods of measurement of earth resistivity are presented with their advantages and limitations.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

TABLE OF CONTENTS

1

LIST OF ILLUSTRATIONS

SECTION 1
INTRODUCTION

A nuclear detonation at very high altitude can produce an extreme-
ly low frequency variation in the earth's magnetic field. The conducting
plasma expanding from the explosion pushes the earth's magnetic field lines
away. The resultant change in magnetic field extends over very large dis-
tances, up to the earth's surface, and is called the Magnetohydrodynamic
Electromagnetic Pulse, MHD EMP.

Since the earth is partially conducting, a changing magnetic field
at its surface will induce eddy currents in the various layers of conducting
strata down to a skin depth. For a given frequency and uniform conducti-
vity, σ, the skin depth is proportional to $1/\sqrt{\sigma}$. The electric field pro-
duced at the surface by a given charge in a magnetic field will be propor-
tional to the resistance of the skin depth layer, i.e., $\alpha/\sqrt{\sigma}$. The problem
is more complicated with a realistic stratified earth but the electric field
is still a function of the earth's conductivity profile.

A long conductor grounded to the earth at one point will exhibit a
potential difference from earth at other points proportional to the electric
field and the distance from the ground point. For practical situations
these potentials can reach hundreds of volts. Vulnerability assessment of
the possibly affected systems and hardening design guidelines require an
evaluation of worst case stresses by:

1) Calculating the worst-case magnetic field changes at the
earth by exoatmospheric nuclear explosions.

3

2)   Determining the earth conductivity profile.

3)   Calculating the worst case voltages induced in specific long-
     line systems (with particular grounding, connectivity, and
     geology).

The objective of this effort relates to the second step: the mea-
surement of the earth conductivity profile over a depth range determined by
the skin depth in the .01 to 10 Hz frequency range. Similar methods are
also useful at higher frequencies (and shallower skin depths) to evaluate
the voltages induced in long cables by nuclear surface bursts. This report
will address primarily the ELF problem of MHD EMP.

Since the MHD EMP wave penetrates the earth to one skin depth the
resistivity must be known to this depth. To measure the bulk resistivity of
the earth one must induce a current in the earth and measure the voltage
drop along the current path. There are several ways currents can be gene-
rated in the earth. The naturally varying magnetic field around the earth
(the magneto-telluric effect) induces current in he earth. Currents can
also be generated artificially by creating an electric field in the earth.
Currents generated both naturally and artificially have been used to measure
the earth's resistivity.

The characteristics of the earth must be understood to develop re-
sistivity measurement methods that will give meaningful results. The char-
acteristics presented here include skin depth considerations, the magneto-
telluric field, the inhomogeneous nature of the earth and the effect of high
conductors on the earth's surface. The two methods most commonly used to
measure the earth's resistivity are the magneto-telluric and the four elec-
trode probe methods. These and a third method developed by Mission Research
Corporation (MRC) are presented. The advantages and limitations of each
method are discussed considering the nature of the MHD EMP wave.

4

SECTION 2
EARTH CHARACTERISTICS

2.1   SKIN DEPTH CHARACTERISTICS

The region of the earth where the resistivity must be known is determined by the depth to which an electric field at a particular frequency will penetrate the earth's surface. This depth of penetration is known as the skin depth and is the distance where the amplitude of the electric field drops to 1/e of its value at the surface. The skin depth (in meters) for a sinusoidal wave is given by

$$\delta = \sqrt{\rho / \pi \, \mu f} \tag{1}$$

where ρ is the resistivity in ohm-m, f is the frequency in Hz and μ is the permeability, $4\pi \times 10^{-7}$ Henry/m. Skin depth curves are shown in Figure 1.

2.2   THE MAGNETO-TELLURIC FIELD

The magneto-telluric field is the time-varying portion of the earth's magnetic field. These fluctuations induce currents that flow in the earth and occur over periods ranging from milliseconds to centuries. A typical amplitude spectrum of magneto-telluric electromagnetic noise is shown in Figure 2. (Ref. 1). This noise is extremely random in character, i.e., noise at one particular frequency may only occur once over a long period of time. In Figure 3 (Ref. 1) typical plots of magneto-telluric current acitivity are shown. When designing techniques to measure resistivity with either magneto-telluric or artificial current sources, the nature of magneto-telluric noise must be considered.

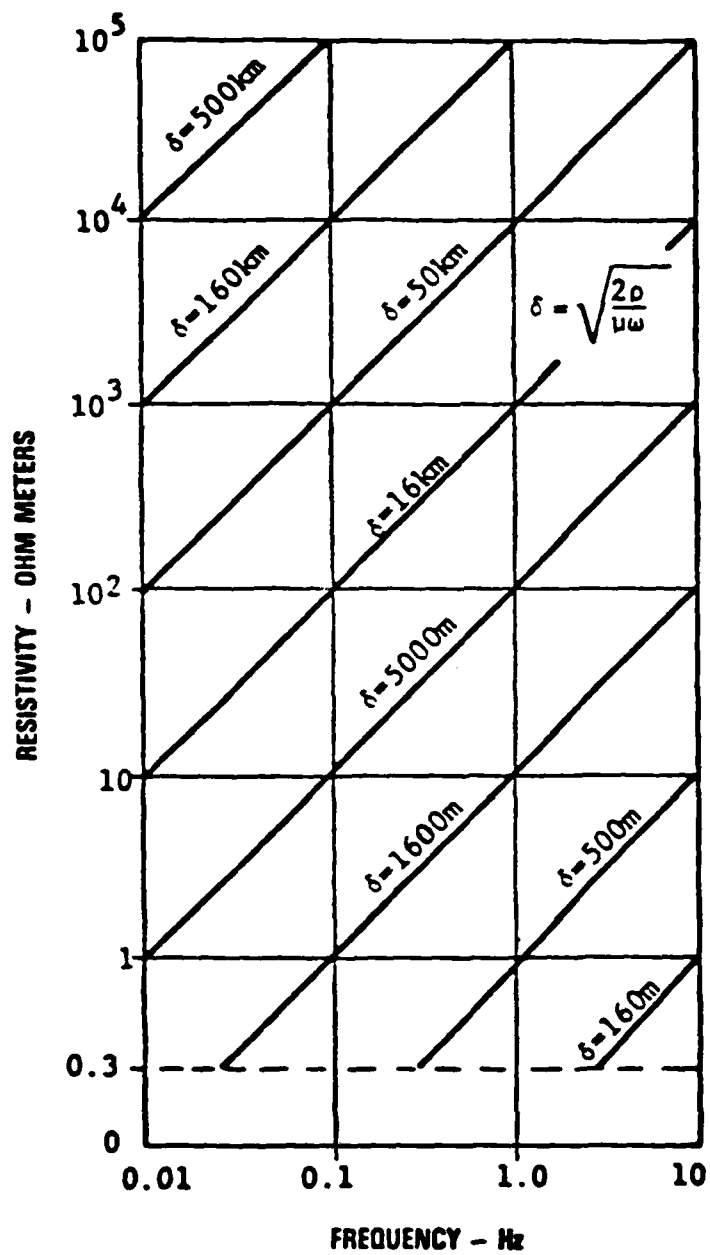1. Keller, et al., Electrical Methods in Geophysical Prospecting, Wiley, N.Y. 1966.

$$\delta = \sqrt{\frac{2\rho}{\mu\omega}}$$
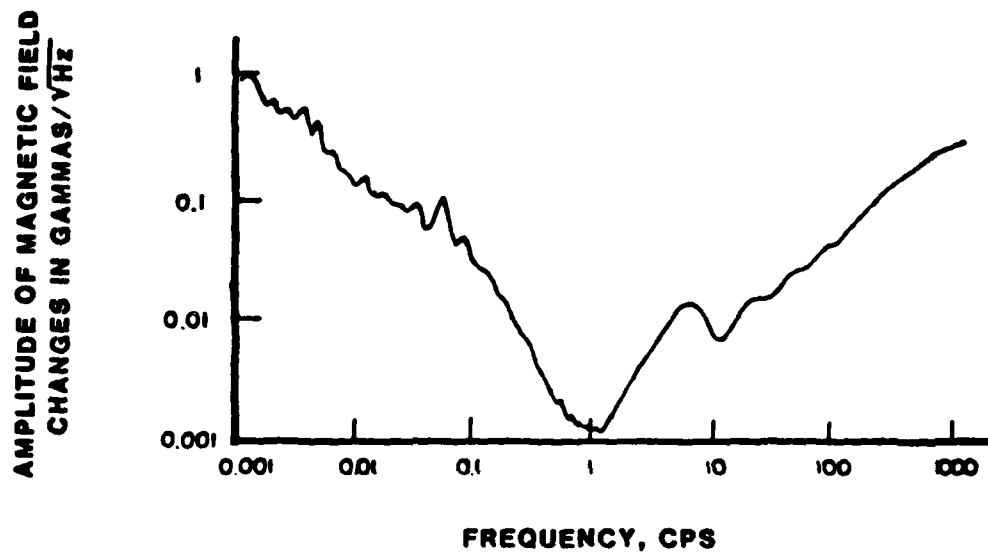
Figure 1. Skin depth curves.

6

Figure 2. Typical spectrum of amplitudes of electromagnetic
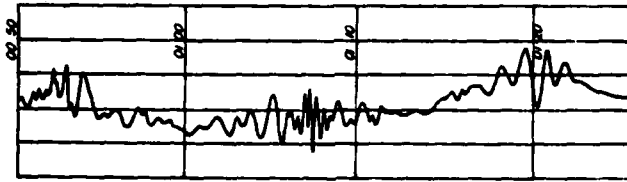noise in the extremely low frequency (elf) range
(Ref. 1).

7

Figure 3. Example of a magneto-telluric signal with transient
micropulsation activity in the 10- to 40-sec period
range. Bergen Park, Colorado, October 11-12, 1962
(Mountain Standard Time). The vertical scale is 10 mV
per km per division.

2.3   THE INHOMOGENEOUS NATURE OF THE EARTH

Any measurements of the earth's resistivity is going to be an ave-
rage over regions of varying resistivities up to one skip depth thickness.
At higher frequencies (small skin depths) variations in water content and
large rocks are responsible for variations in resistivity. The resisitivity
ranges of several rock types are shown in Figure 4 (Ref. 2). At lower fre-
quencies (large skin depths) the earth's resistivity is more dependent on
major geologic formations and underground streams. Figure 5 (Ref. 2) is a
resistivity map of the United States at 10 KHz. Measuring the resistivity
at a particular depth is a formidable task, however the MHD EMP wave aver-
ages the resistivity over one skin depth. The wave not only averages in
depth but also in area. The resolution of the wave can be approximated as
an area one skin depth deep by two skin depths wide. A meaningful measure-
ment will be obtained if it simulates the MHD EMP wave in terms of its reso-
lution and averaging properties.

---

2. "Experimental Study to Make MHD/EMP Effects Predictions from Geomagnetic
Storm Data," GTE Sylvania meeting at DNA, 13 July 1979.

Ω m

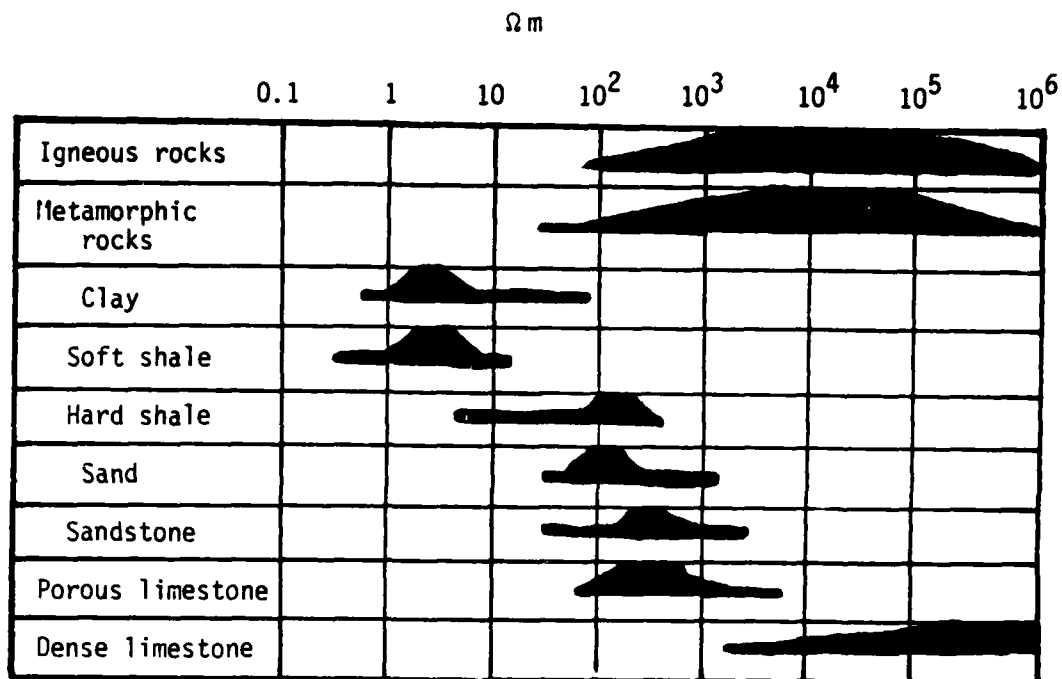|	0.1	1	10	10^2	10^3	10^4	10^5	10^6
Igneous rocks								
Metamorphic rocks								
Clay								
Soft shale								
Hard shale								
Sand								
Sandstone								
Porous limestone								
Dense limestone								

Figure 4. Approximate resistivity ranges of some rock types. The resistivity scale (horizontal) is logarithmic.

2.4 THE EFFECT OF HIGH CONDUCTORS ON THE EARTHS SURFACE

Any good conductors (power lines, railroad tracks, etc.) within the resolution area of the MHD EMP wave will tend to short out a portion of the field and lower the electric field strength surrounding the buried cable of interest by lowering the effective resistivity of the earth. If the effective resistivity of a particular location is desired, then good conductors in the area are indeed a part of the picture and no correction for them is needed when making measurements; however, if the resistivity of the earth itself is desired, good conductors will cause a substantial error in the measurement. The highest electric fields will appear at the surface when the number of nearby good conductors is a minimum, for this reason an area of at least two skin depths wide with no, or very few, conductors is desired for an accurate measurement.
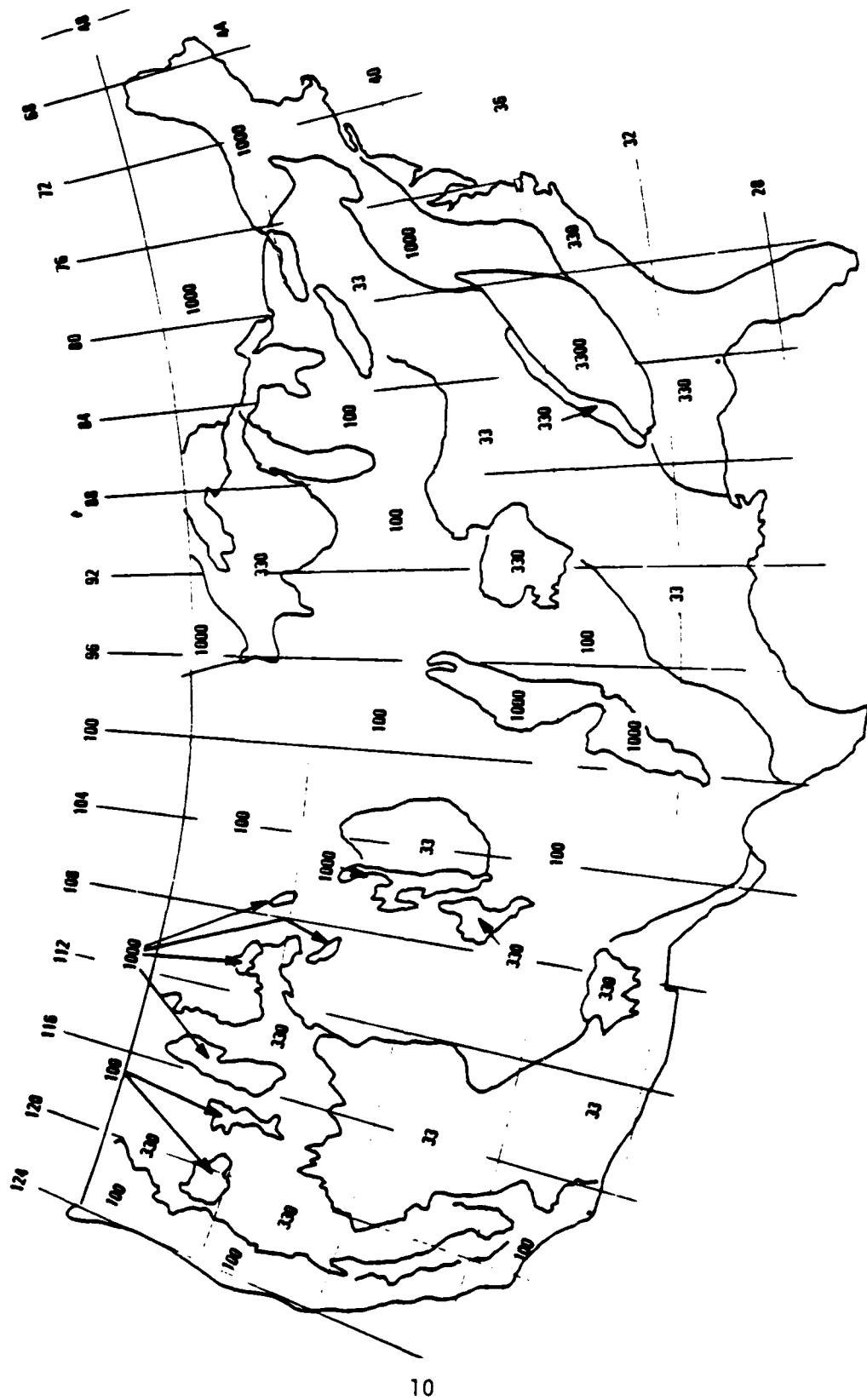
9

Figure 5. Average resistivity at 10 kHz for the United States Ω-m.

SECTION 3
THE FOUR ELECTRODE PROBE METHOD

One difficulty encountered when artificially inducing currents in the earth with electrodes is that there is a contact resistance between the earth and an electrode. In the equivalent circuit shown in Figure 6 the contact resistance (R_c) and the resistance of the earth (R_e) cannot be separated. The four electrode probe method solves this problem by setting up a dipole current field with two probes and measuring the voltage with the other two probes as shown in Figure 7.
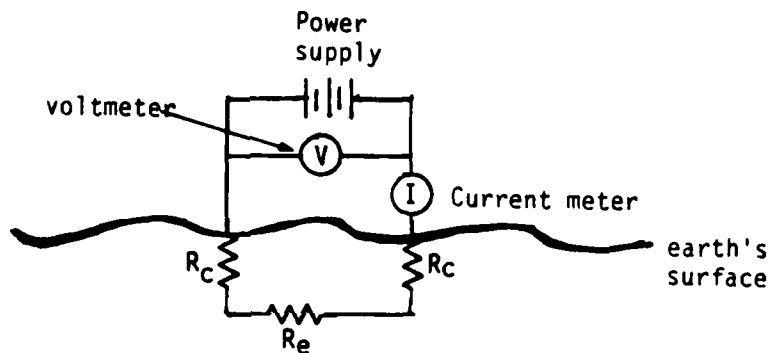
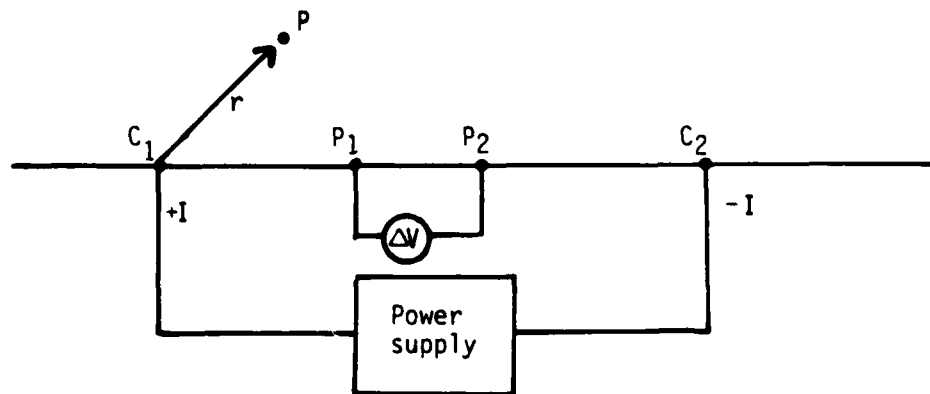Figure 6. Equivalent circuit showing earth contact resistance.

Figure 7. Four electrode probe geometry.

11

Contact resistance losses only occur where current flows at C_1 and C_2, not at P_1 and P_2 where virtually no currrent flows. The current flows radially in a hemispherical distribution out of C_1 and similarly into C_2 for earth of uniform resistivity, ρ. The current distribution and equipotentials are shown in Figure 8. The current density, j, at a distance, r, from C_1 is

$$j = I/2\pi r^2 \tag{2}$$

where I is the total current injected at C_1. The potential gradient is

$$-\frac{\partial V}{\partial r} = \rho j = \rho I/2\pi r^2. \tag{3}$$

Integrating, the potential at distance r is obtained

$$V = I\rho/2\pi r \tag{4}$$

The potential difference due to the current source C_1 between P_1 and P_2 is

$$V = \frac{-I\rho}{2\pi}\left(\frac{1}{C_1 P_1} - \frac{1}{C_1 P_2}\right) \tag{5}$$

Similarly the potential difference between P_1 and P_2 due to the current sink, C_2 is

$$V = \frac{-I\rho}{2\pi}\left(\frac{1}{C_2 P_1} - \frac{1}{C_2 P_2}\right). \tag{6}$$

Summing these two voltages the resultant voltage between P_1 and P_2 is,

$$\Delta V = \frac{I\rho}{2\pi}\left(\frac{1}{C_1 P_1} - \frac{1}{C_1 P_2} - \frac{1}{C_2 P_1} + \frac{1}{C_2 P_2}\right). \tag{7}$$
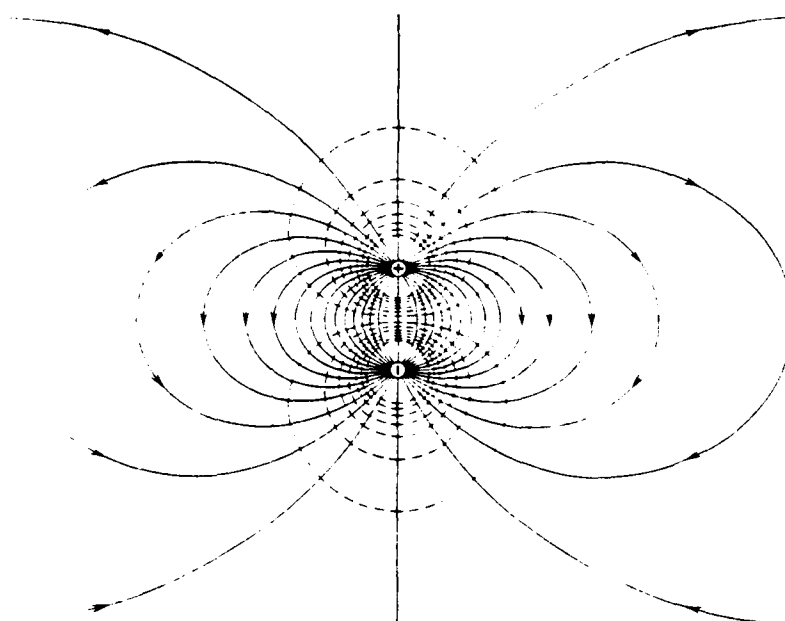
12

Figure 8. Current distribution and equipotentials for a uniform earth as viewed from above the surface.

13

Substituting K for the expression in the brackets and solving for the resistivity, ρ, one obtains,

$$\rho = 2\pi \, \frac{\Delta V}{IK} \, . \tag{8}$$

Several important assumptions have been made in the development of this solution and the method in general. The most important of these is that the earth under consideration is homogenous. Consider the possiblity that the resitivity of the earth varied as shown in Figure 9 (Ref. 3). This lowers the current density at the probes, lowering the voltage and the calculated resistivity. This error could be substantial if the resistivity nearby is very low.

A second important assumption is that the injector probes, C_1 and C_2, are separated by less than one skin depth, resulting with a dipole field distribution. If the separation is less than one skin depth the current will not penetrate into the earth up to a skin depth. If the separation is larger than one skin depth the field distribution is no longer a simple dipole distribution. The current field distribution in a homogeneous medium for current probes separated by several skin depths is shown in Figure 10. Corrections can be made for a non-dipole current distribution, however for the separation required to simulate the skin-depths of the MHD EMP wave the earth is far from homogeneous and the result would still be in error. For these reasons the four electrode probe method is generally used to examine relative surface soil conditions for agricultural purposes. It would be a poor choice for this particular problem.

---

3. Sharma, P.V., Geophysical Methods in Geology, Elsevier, N.Y. 1976.

Figure 9. Lines of current flow (continuous curves) and
equipotentials (dashed curves) due to a pair of
point electrodes on the earth's surface. A good
conductor will perturb the equipotentials and
current flow as shown. For reasons of clarity the
potential difference between adjacent equipotentials
is not the same. If it were, the equipotentials would
be tightly crowded near the electrodes and farther
apart in the center.

15

Figure 10. Current distribution for current injection probes separated by several skin depths in an homogeneous media.

SECTION 4
THE MAGNETO-TELLURIC METHOD

The time varying magneto-telluric field induces current in the earth. If the potential difference developed along a current path and the magnetic field strength, H, can be measured, the resistivity to one skin depth can be calculated. Similar to the M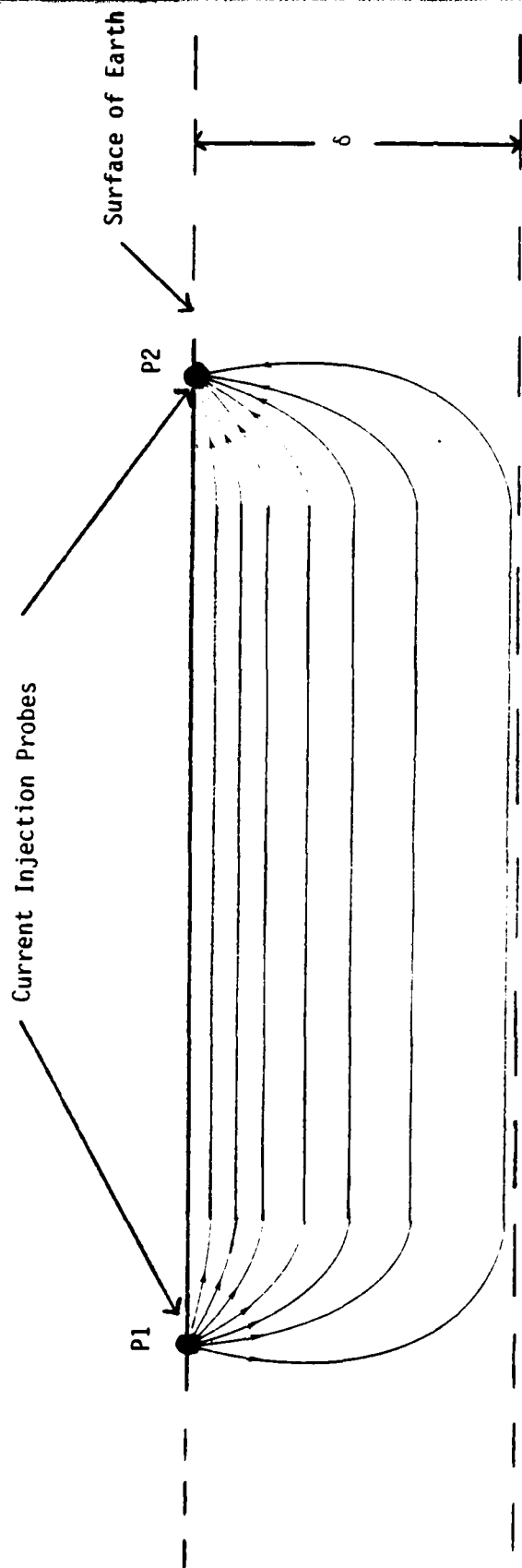HD EMP wave, the magneto-telluric field penetrates the earth one skin depth. This will, by Faraday's law, induce a slab of current in the earth one skin depth deep and many skin depths wide. The current density for this geometry is given by

$$ j = \frac{2H}{(1.257 \times 10^3)\ \delta} \tag{9} $$

where j is the current density in amps/m^2, δ is the skin depth in meters and H is the magnetic field strength in gammas.

By making the appropriate substitutions for δ and j the resitivity is given by

$$ \rho = \left(\frac{E}{H} \right)^2 \frac{0.2}{f} \tag{10} $$

where E is the measured electric field strength in mV/km and f is the frequency in Hz. Due to the vectorial relationship between H and j, the magnetic field must be measured orthogonal to the electric field.

To assure that all signals are observed the arrangement of electrodes and magnetometer as shown in Figure 11 is used. (A magnetometer is

a device that measures the magnetic field.) This results in a resistivity in two different directions, x and y where

$$\rho_x = \left(\frac{E_x}{H_y}\right)^2 \frac{0.2}{f} \qquad\qquad (11)$$

and

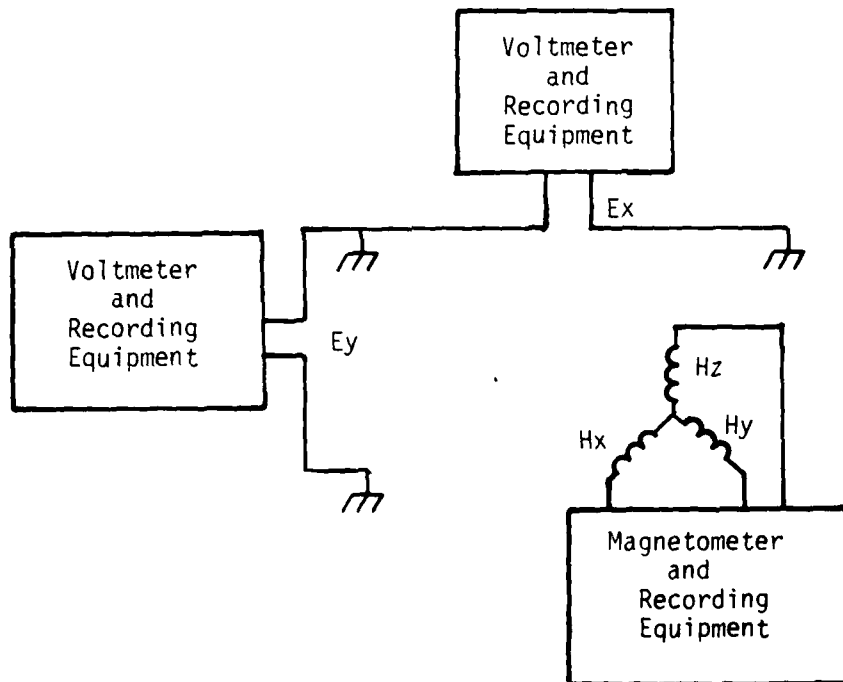$$\rho_y = \left(\frac{E_y}{H_x}\right)^2 \frac{0.2}{f} . \qquad\qquad (12)$$

Figure 11. Configuration for the magneto-telluric measurement method.

18

The magneto-telluric field is very noisy, as mentioned earlier, so special techniques must be used to interpret the data. The simplest method is to measure the period of various oscillations and use this for the frequency as required in equations (11) and (12). Keller (Ref. 1) does this with marginal success as shown in Figure 12 and Table 1. This data shows the limitations in obtaining data at a desired frequency, as the results are random in frequency. To obtain more data one can use a computer to take Fourier transforms of the wave forms. A typical resistivity spectrum as derived by taking transforms of the wave forms is shown in Figure 13 (Ref. 2). These data are inconclusive due to the noise on the spectrum.

One serious problem with the magneto-telluric method for this particular application is that the frequency range of the MHD EMP wave is in an area where the amplitude of the magneto-telluric noise is small, as shown in Figure 2. However, were it not for the random nature of the magneto-telluric noise, this method has significant advantages over the four electrode probe method. There is no problem with skin depth considerations, as the magneto-telluric field is wide spread, creating a slab of current. Since the resolution of this method is determined by the skin depth, as described earlier, the effects of higher conducting regions and high conductors more than one skin depth away form the point of measurement can be neglected. Considering the above, this method is seriously limited for this particular frequency range.

Figure 12. Record of magneto-telluric field variations used for computing apparent resistivity. The numbers indicate consecutive half-periods of the oscillations picked from the record.

Table 1. Keller's Data.

Number of event	H_y gammas	E_r mV/km	T sec	ρa ohm-m	$\sqrt{T}$
1	4·55	6·85	42	19·1	6·48
2	3·52	8·55	30	35·2	5 48
3	1·97	3·88	10	7·8	3·16
4	7·21	13·7	23	16·6	4·80
5	9·62	19·9	50	42·8	7·08
6	3·84	8·05	17	15·0	4·12
7	5·76	13·8	38	43·8	6·16
8	3·26	6·39	16	12·3	4·00
9	3·12	6·85	28	27·1	5·30
10	2·76	5·41	16	12·3	4·00
11	1·49	3·52	13	14·5	3·61
12	2·76	5·02	12	8·0	3·46
Average				21·2	4·39

20

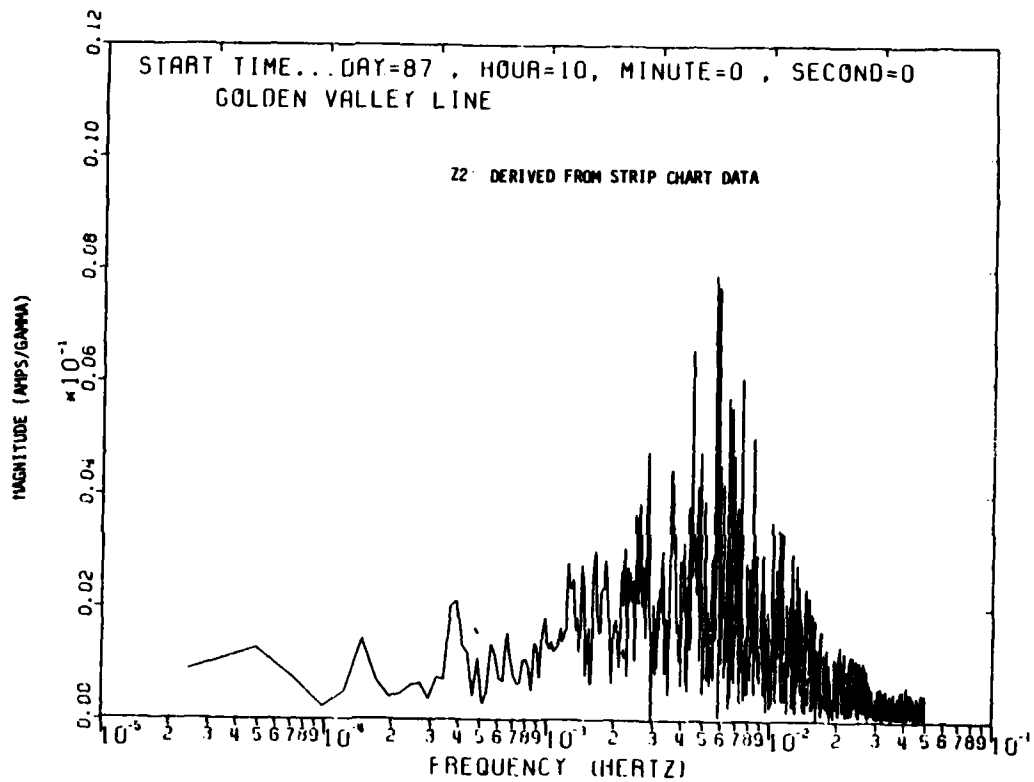Figure 13. Poker flat magneto-telluric data Z2 impedance
estimate.

21

SECTION 5
AC MEASUREMENT METHOD

5.1   APROACH AND DESIGN CALCULATIONS

The limitations of the four electrode probe and the magneto-tellu-
ric methods are of a different nature. This fact enables one to develop a
measurement method which combines the two methods in such a way that the
limitations of each method are eliminated. This is accomplished by generat-
ing a current field with electrodes separated by several skin depths at the
lowest frequency of interest. The two injection points are connected by a
straight conductor near the surface of the earth (much closer than a skin
depth), but insulated from it. Since the conductor must be very long
($\approx$100 km) it is chosen to be an existing conductor, such as a communication
wire or power line. Current is injected along the conductor and into the
earth at various frequencies spanning the range of interest.

At a given frequency the current distribution in the earth will be
as illustrated in Figure 10, i.e., far away from the injection points it
will extend downward and sideways approximately one skin depth. Since the
fields are falling off sideways from the conductor, the ratio of electric
and magnetic field is not equal to the value for uniform planar excitation
as given in equation 10. The values of Hz and E_x as a function of dis-
tance, y, away from the conductor at the surface of a uniformly conducting
earth have been calculated by Patra and Mallick (Ref. 4). Their result is

---

4. H.P. Patra and K. Mallick, "Time-Varying Geolectric Soundings", Elsevier
    Scientific Pub., 1980.

22

$$\frac{H_z}{H_0} = \frac{2}{i\rho^2}\left[2 - 2\ \rho\sqrt{i}\ K_1(\rho\sqrt{i}) - i\rho^2 K_0(\rho\sqrt{i})\right] \qquad (13)$$

$$\frac{E_x}{E_{xo}} = \frac{2}{i\rho^2}\left[1 - \rho\sqrt{i}\ K_1(\rho\sqrt{i})\right] \qquad (14)$$

where

$H_0 = I/2\pi y$

$E_0 = -i\omega\mu I/2\pi$

$\rho = y\sqrt{\mu\omega\sigma}$

σ = earth conductivity

μ = earth permeability

ω = angular frequency

I = wire current

K_0, K_1 = modified Bessel functions

H_0 is the magnetic field that would exist around the wire at distance y in the absence of a conducting earth. E_0 is simply a convenient normalization factor. Near the conductor, ($y < 1/\sqrt{\mu\omega\sigma}$) H_z approaches H_0, independent of soil resistivity. Near the conductor E varies as log y with a coefficient that is dependent on σ. Figures 14 and 15 illustrate the variation of electric and magnetic fields with ρ.

From these formulas the equivalent uniform resistivity of the earth can be derived in principal from measurements of the amplitude or phase of the electric or magnetic fields at any point in the region excited by the conductor. Limitations are imposed by nonuniformities in the excited region and the signal-to-noise ratio of the excitation.
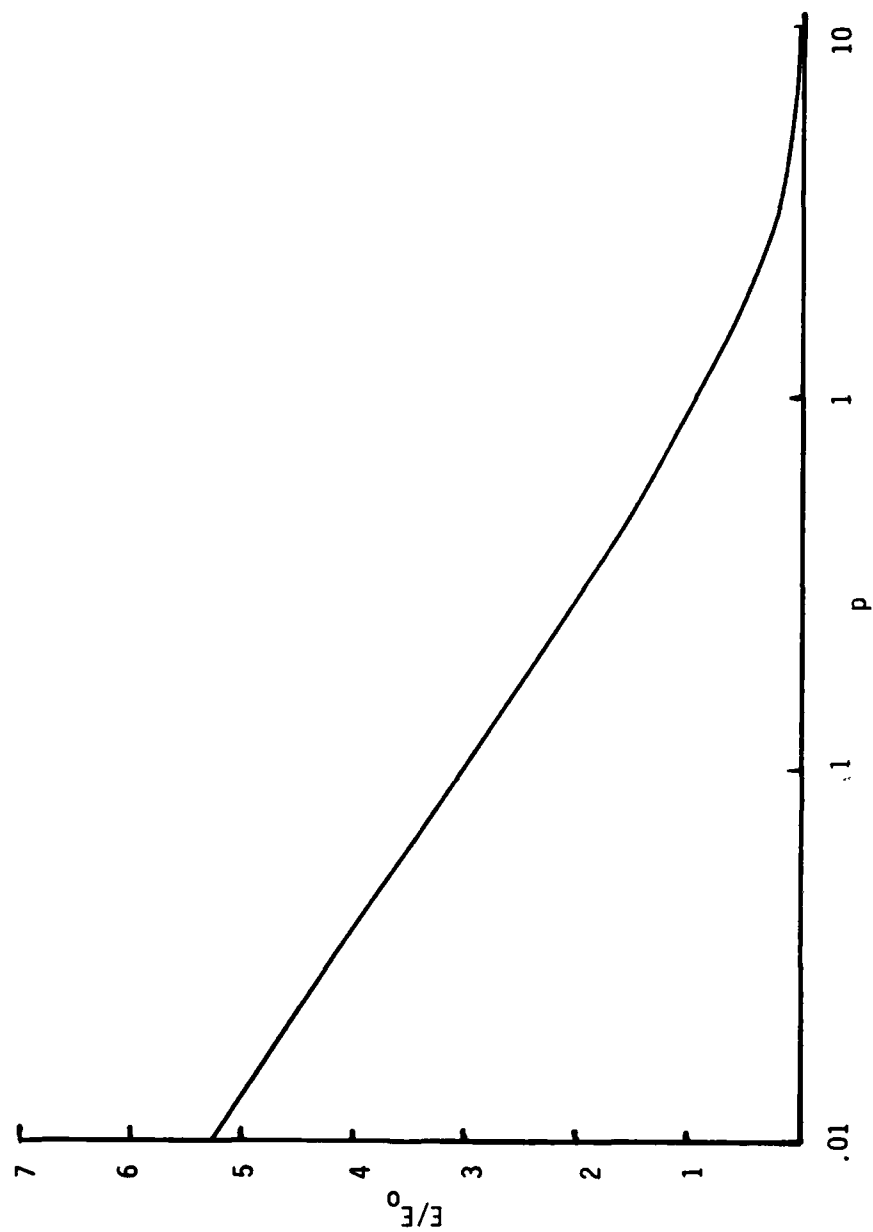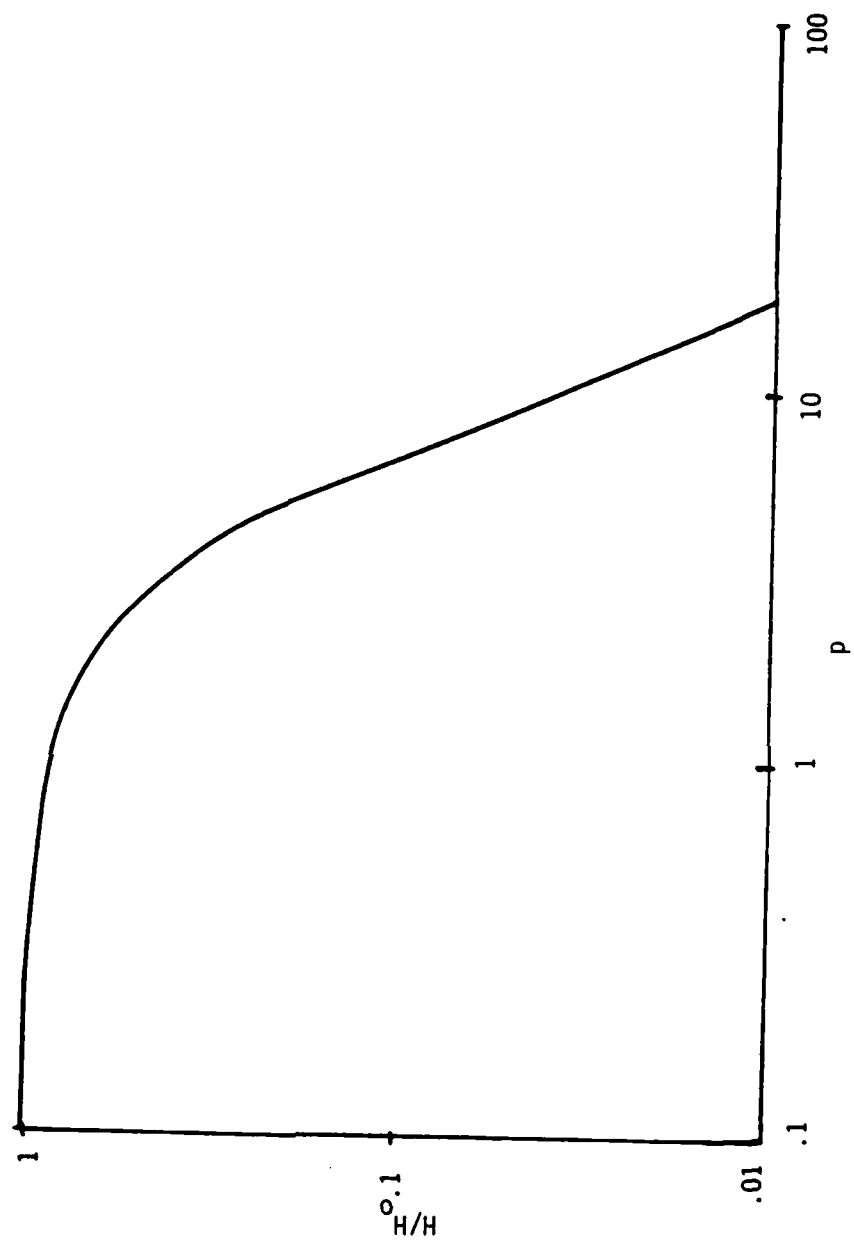
Figure 14. E/E_0 vs. p.

24

Figure 15. H/H_s vs. p.

25

The electric field in the earth near the conductor is $E \approx 10\, E_o$, requiring a voltage between the ends of the conductor of $V_e \approx -i10\omega\mu IL/2\pi$, where L is the conductor length in meters. In addition, the power supply must overcome the resistive loss in the conductor. Assuming a resistance of 0.4 Ω/km, this loss is $V_c \approx 4 \times 10^{-4}\, L$. At low frequencies ($\omega < 10\, s^{-1}$) the resistive loss in the wire dominates the power supply voltage requirement.

A reasonable measurability criterion is that the electric and magnetic fields produced by the current induced into the earth should be at least equal to the natural magneto-telluric fields at the same frequency. If this condition is satisfied the lock-in technique can easily extract the signal due to current injection from the magneto-telluric background.

The magneto-telluric noise is represented by the curve H(f) in Figure 2. This will introduce a magnetic field at the measurement location of $\Delta H = H(f)\, \sqrt{\Delta f}$, where Δf is the measurement bandwidth. It will also produce an electric field of

$$\Delta E = \Delta H \sqrt{\frac{\mu\omega}{2\sigma}} \tag{15}$$

The current must be sufficiently large to make the impressed field comparable to the magneto-telluric field. In order to deduce the soil resistivity from magnetic field measurements, its necessary to measure H at large enough distances, such that $H/Ho < .8$, or $\rho > 1$. Thus, since for $\rho = 1$ then $y = 1/\sqrt{\mu\omega\sigma}$

$$1 > H(f)\, \sqrt{\Delta f}\; (2\pi y)$$

$$> 2\pi\, H(f) \sqrt{\frac{\Delta f}{\sigma\mu\omega}} \tag{16}$$

26

The electric field can be measured at any distance from the wire to determine the resistivity. Its value is $\approx \mu\omega I/2\pi$. Thus, for a signal nosie ratio of at least

$$I > H(f)\sqrt{\frac{\mu\omega \ \Delta f}{2\sigma}}\left(\frac{2\pi}{\mu\omega}\right) \tag{17}$$

$$> \Pi \ H(f)\sqrt{\frac{2\Delta f}{\sigma\mu\omega}}$$

Since this is a factor of $\sqrt{2}$ less than the criterion on the current derived for magnetic field measurements, we will use the former criterion.

For example, if $\sigma = 10^{-3}$ s/m, $f = 0.1$ Hz, $\Delta f = 10^{-2}$ Hz, and from Figure 2, $H(f) = .05 \ \gamma$ at 0.1 Hz.

$$I > 2\pi \times .05 \times 8 \times 10^{-4}\sqrt{\frac{10^{-2}}{10^{-3} \times 4\pi \times 10^{-7} \times 2\pi \times 0.1}} \tag{18}$$

$$> 0.9 \ A$$

5.2   MEASUREMENT SYSTEM

A candidate measurement system is illustrated in Figure 16. Two components of the electric field and three components of magnetic field are measured as a check on uniformity and self consistency. This redundancy can also be used to unfold a measure of the spatial distribution of earth resistivity.

The measuring instruments are phase-locked to the current source to improve the signal-to-noise ratio. Each measurement is performed with and without current injected into the earth to check the signal-to-noise
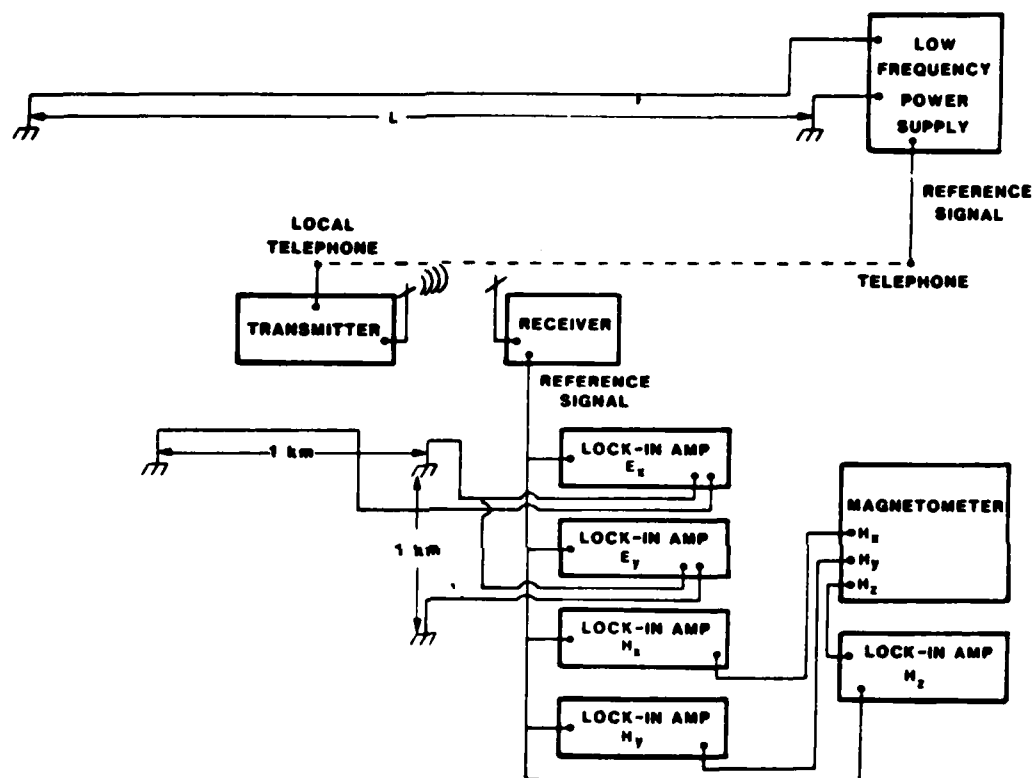
27

Figure 16. Low frequency conductivity measurement.

ratio. The reference signal will be brought form the current source to the measurement location by a combination of telephone and local transmitter-receiver (radio or fiber optics) links.

Two types of phase locked detection systems will be used. Lock in amplifiers are used at frequencies greater than 0.1 Hz. At frequencies between 0.1 Hz and 0.01 Hz an analog to digital converter fed into magnetic tape will be used. The data will be unfolded using a computer at a later time. Low bandwidths achieved using these techniques are limited only by the length of the recording time.

The smaller bandwidth at the lowest frequency is achieved by using an analog to digital convertor fed into magnetic tape. The magnetic tape will record three axis of the magnetic field, two axis of the electric field and the reference signal. The A/D converter must handle 20 samples/s at 10 bits per sample. The tape must record 500 bits/s. This results with one 10,000 foot roll of tape per 24 hours. Bandwidths as low as 1.16×10^{-5} Hz can be achieved. Figure 17 shows the layout of the measurement using magnetic tape. The magnetic tape will be analyzed using a computer. The analysis will involve averaging the in-phase signals over the time equal to the inverse of the bandwidth. From these values the resistivity can be calculated. The signals will also be analyzed in quadrature, 90 degrees out of phase with the signal. This will establish the noise within the bandwidth. if the magneto-telluric noise is large enough, the resistivity can also be calculated from its signal. It is expected that between 0.1 Hz and 10 Hz the noise will be so low that any resistivity measurement resulting from noise would not be very accurate. At lower frequencies the noise could rise to an acceptable level to act as either a check on the driver signal result or, if the noise is larger, a more accurate result. Either way, large, moderate or small noise, a meaningful measurement will be obtained.
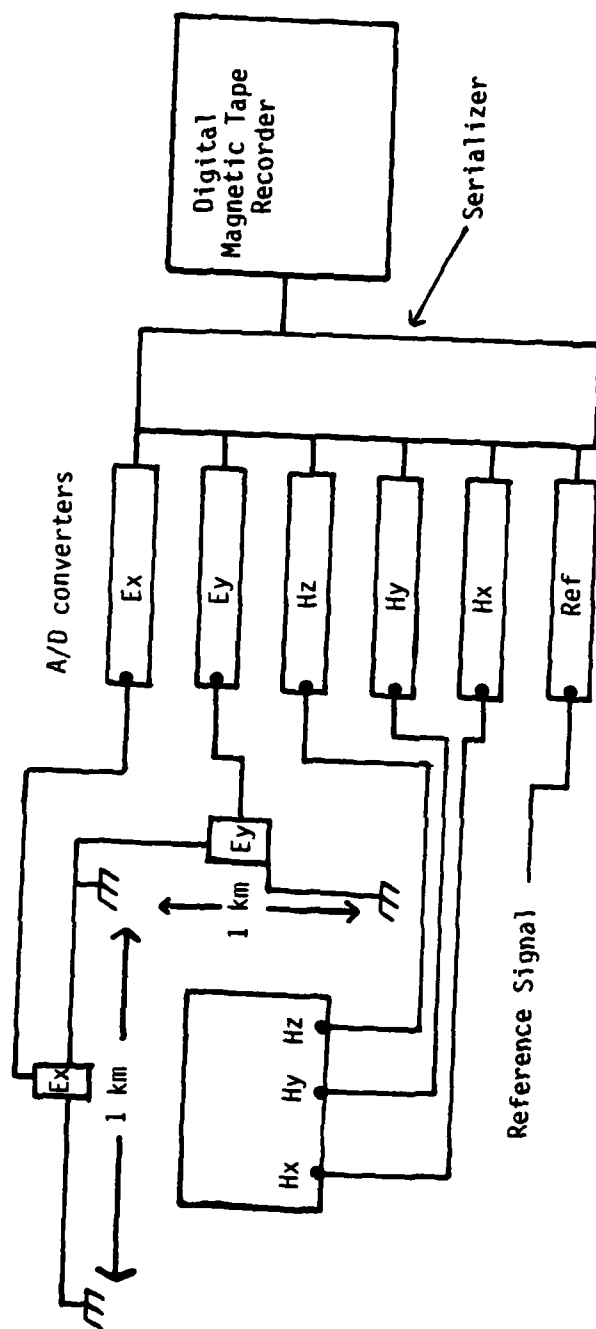
Figure 17. Measurement station using magnetic tape.

This is not the only check on internal consistency in this measurement technique. Since the electric fields and phases are both measured each will generate a result which can be compared. Furthermore, the measurement can be performed at various locations in the excitation field.

5.3 POWER REQUIREMENTS

Table 2 presents the current and power required for electric and magnetic field measurements using, a separation between injection points of $10 \times \delta$ in low conductivity ($\sigma = 10^{-3}$ S/m) earth. The voltage is dominated by the conductor resistance at these frequencies (assumed to be 0.4 Ω/km).

The power requirements are very modest down to $f = 0.1$ Hz. At 0.01 Hz the power limitations become high, although achieveable with off-the-shelf power amplifiers. The power increases because the current must increase to overcome H(f) and the conductor resistance is high. Some amelioration is possible by relaxing the requirement that the injection be separated by ten skin depths.

Table 2
Current and Power Requirements
S:N = 1:1; space = 10 δ; 10^3 Ω m earth

Frequency (Hz)	Skin Depth (k/m)	H(f) (γ/Hz)	Injection Separation	Δf(Hz)	I(A)	V(V)	P(W)
10	5	0.01	50	10^{-2}	0.02	0.4	0.008
1	16	0.002	160	10^{-2}	0.01	0.6	0.006
0.1	50	0.05	500	10^{-2}	0.9	180	160
0.01	160	0.5	1600	10^{-4}	2.8	1800	5000

31

5.4 LOCATION REQUIREMENTS

An area free of good conductors over the entire dimensions of the field probably does not exist. Fortunately, if there are smaller regions of the field free of good conductors, the measurement can be performed with little difficulty. This area must be one voltage probe separation long, along the injection electrode axis and two skin depths wide. Any conductors outside this area will have little to no effect on the measurement. Several such areas must exist in the field so that several measurements can be made.

SECTION 6
CONCLUSION AND RECOMMENDATION

To determine the response of a buried cable to an MHD EMP wave measurement method with the greatest accuracy must be chosen. The four electrode probe and the magneto-telluric methods have fundamental limitations. The AC method proposed by MRC overcomes these limitations. A survey should be conducted to locate conductors of adequate length and conductivity in a desirable location relatively free of interfering conductors. Once a good cable and location are found the AC measurement method could be performed.

DISTRIBUTION LIST

DEPARTMENT OF DEFENSE

Defense Communications Agcy
    ATTN: Code 312
    ATTN: Code C313

Defense Communications Engr Ctr
    ATTN: Code R123
    ATTN: Code R400
    ATTN: Code R720, C. Stansberry

Defense Intelligence Agcy
    ATTN: RTS-2A
    ATTN: DB-4C2, D. Spohn

Defense Nuclear Agcy
    ATTN: RAEV
2 cy ATTN: RAEE
2 cy ATTN: DDST, V. van Lint
4 cy ATTN: TITL

Defense Tech Info Ctr
12 cy ATTN: DD

Field Command
Defense Nuclear Agcy
    ATTN: FCLMC, H. Putnam
    ATTN: FCPR
    ATTN: FCTXE
    ATTN: FCTT
    ATTN: FCTT, W. Summa
    ATTN: FCTT, G. Ganong

DEPARTMENT OF THE ARMY

BMD Systems Cmd
    ATTN: BMDSC-AOLIB
    ATTN: BMDSC-HLE, R. Webb

DEPARTMENT OF THE AIR FORCE

Air Force Wpns Lab
    ATTN: NTYEE, C. Baum
    ATTN: NTYC, M. Schneider
    ATTN: CA
    ATTN: NXS
    ATTN: NTYEP, W. Page
    ATTN: NT
    ATTN: SUL
    ATTN: NTN

Air University Library
    ATTN: AUL-LSE

Ballistic Missile Office
    ATTN: ENSN, W. Wilson
    ATTN: M. Stapanian
    ATTN: ENSN, W. Clark

DEPARTMENT OF DEFENSE CONTRACTORS

BDM Corp
    ATTN: Corporate Library

BDM Corp
    ATTN: Library

DEPARTMENT OF DEFENSE CONTRACTORS (Continued)

Boeing Co
    ATTN: Kent Tech Library
    ATTN: D. Kemle
    ATTN: H. Wicklein
    ATTN: B. Hanrahan

Dikewood
    ATTN: Tech Library for C. Jones
    ATTN: Tech Library
    ATTN: Tech Library for L. Davis

Electro-Magnetic Applications, Inc
    ATTN: D. Merewether

International Tel & Tel Corp
    ATTN: A. Richardson
    ATTN: Tech Library

JAYCOR
    ATTN: D. Higgins
    ATTN: W. Hobbs
    ATTN: W. Radaski

Kaman Tempo
    ATTN: W. McNamara
    ATTN: DASIAC
    ATTN: R. Rutherford

McDonnell Douglas Corp
    ATTN: S. Schneider
    ATTN: Tech Library Svcs

Mission Research Corp
    ATTN: EMP Group
    ATTN: W. Crevier
2 cy ATTN: C. Longmire
5 cy ATTN: Doc Con

Mission Research Corp
    ATTN: A. Chodorow
    ATTN: L. McCormick

Mission Research Corp
    ATTN: B. Passenheim
4 cy ATTN: J. Erler

Mission Research Corp
    ATTN: W. Ware
    ATTN: J. Lubell
    ATTN: W. Stark

Pacific-Sierra Research Corp
    ATTN: L. Schlessinger
    ATTN: H. Brode, Chairman SAGE

R&D Associates
    ATTN: M. Grover
    ATTN: C. Mo
    ATTN: Doc Con
    ATTN: W. Graham
    ATTN: W. Karzas

Science & Engrg Assoc, Inc
    ATTN: V. Jones